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Chapter 4

Designing a Methodology for Future Air Travel Scenarios

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INTRODUCTION

The growing demand on air travel throughout the world has prompted several proposals for the development of commercial aircraft capable of transporting a large number of passengers at supersonic speeds. Emissions from a projected fleet of such aircraft, referred to as high-speed civil transports (HSCTs), are being studied because of their possible effects on the chemistry and physics of the global atmosphere, in particular, on stratospheric ozone. At the same time, there is growing concern about the effects on ozone from the emissions of current (primarily subsonic) aircraft emissions.

Evaluating the potential atmospheric impact of aircraft emissions from HSCTs requires a scientifically sound understanding of where the aircraft fly and under what conditions the aircraft effluents are injected into the atmosphere. Multi-dimensional 2-D and 3-D models of the global atmospheric chemical, radiative, and dynamical processes are the primary tools used to assess the impact of such emissions.

Assessments of the understanding of the potential effects on the atmosphere will be made periodically. This report presents a preliminary set of emissions scenarios. A more complete assessment of the environmental impact of emissions from a commercially viable, reasonably mature fleet of HSCTs will be conducted in about 2 years. At that time, more realistic scenarios of both existing and projected future aircraft emissions will be needed for evaluation with state-of-the-art 2-D and 3-D global atmospheric models. These scenarios will be used to understand the sensitivity of environmental effects to a range of fleet operations, flight conditions, and aircraft specifications.

This chapter provides the baseline specifications for the scenarios: the criteria to be used for developing the scenarios are defined, the required database for initiating the development of the scenarios is established, and the state-of-the-art for those scenarios that already have been developed is discussed. This project will be continued in preparing for the next major assessment, and will be described in the next High-Speed Research Program/Atmospheric Effects of Stratospheric Aircraft Program Report.

An important aspect of the assessment will be the evaluation of realistic projections of emissions as a function of both geographical distribution (i.e., latitude and longitude) and altitude from an economically viable commercial HSCT fleet. With an assumed introduction date of around year 2005, it is anticipated that there will be no HSCT aircraft in the global fleet at that time (assuming that the Concordes have all been retired). However, projections show that, by 2015, the HSCT fleet could reach significant size. We assume these projections of HSCT and subsonic fleets for about 2015 can then be used as input to global atmospheric chemistry models to evaluate the impact of the HSCT fleets, relative to an all-subsonic future fleet. This chapter discusses the methodology, procedures, and recommendations for the development of future HSCT and the subsonic fleet scenarios used for this evaluation.

Boeing and McDonnell Douglas have been instrumental in developing the scenarios examined thus far within the NASA HSRP program. Both companies have special modeling capabilities to determine the emissions from a commercial aircraft fleet. (Note: Within the United States, the Analytical Technology Applications Corporation has developed a similar capability for the Federal Aviation Administration (FAA), but this model has not yet been used in developing emission scenarios for assessment studies.) Boeing and McDonnell Douglas made different assumptions in developing their scenarios.

SPECIAL CONSIDERATIONS TO SCENARIO DEFINITION

The general methodology for calculating realistic emission scenarios for both subsonic and HSCT fleets consists of several components.

1. Marketing projections would be made of the demand for air travel between cities (i.e., city-pairs) in the form of available seats per city-pair. This analysis would also consider the likely (conceptual) aircraft and the frequency of such flights (note that the frequency will likely depend on aircraft seating capacity, flight speed, and turnaround time).

2. For a given aircraft concept, a performance analysis of the aerodynamics and propulsion system would be done to determine the fuel consumption as a function of aircraft weight, range, engine power setting, and flight segment (e.g., taxi-idle, takeoff, climb, cruise, approach).

3. Fuel consumption would be determined as a function of geophysical distribution and altitude calculated by "flying" the aircraft along the routes between the city-pairs. Special features, such as supersonic flight only over water, waypoint routing, weather, environmental optimization, etc., can be incorporated at this stage.

4. Emissions would be calculated. While these will always be proportional to fuel consumption, emission indices (EIs) of some species such as NO_x, CO, and hydrocarbons will vary with the flight segment.

There may also be small corrections resulting from flight altitude, humidity, and air temperature. More detailed discussions of each of these topics, as they relate to scenario definition, is given later.

MARKETING ASSUMPTIONS

International air transportation is expected to increase steadily from now through the year 2015. During this time, the available seat miles (ASM, mileage between city-pairs determined by great circle route) is expected to increase from 1.6×10^{12} ASMs/year in 1987 to about 5×10^{12} ASMs/year in 2015 as shown in Figure 1 (1). Approximately $2.1\text{-}2.5 \times 10^{12}$ ASMs/year will be in long-range flights by 2015. It is assumed that the total ASMs will be approximately conserved when the HSCT is introduced, and that the HSCT will displace some of the long-range subsonic ASMs. The extent of displacement and the particular routes chosen for HSCTs, however, will depend strongly on the economics of the HSCT.

A viable HSCT fleet must be technologically feasible as well as profitable for the airline that uses it. This means that the operating costs of the HSCT must compete with those of current or future subsonic aircraft. These costs will depend on the characteristics of the aircraft (e.g., technology required, specific fuel consumption, range, capacity, and speed). Marketing studies show that the economic demand for a specific fleet size of HSCTs depends strongly on the operating costs relative to those of subsonic aircraft. In the most optimistic case, in which supersonic fares are assumed to be nearly the same as subsonic fares, the demand for an HSCT consisting of as many as 900 aircraft would be a reasonable assumption, by the year 2015 (1). As HSCT operating costs (and ticket prices) rise, the projected fleet size decreases. However, projections indicated that a minimum fleet size - 300 to 500 HSCTs - would be necessary to induce the airframe industry to develop an HSCT. An optimistic, but realistic, baseline scenario for assessing the atmospheric effects of an HSCT fleet in 2015 would be about 500 aircraft.

Performance Calculations

For a given aircraft or aircraft concept, aerodynamic and propulsion system analyses are done to calculate the fuel consumption as a function of aircraft weight, engine characteristics, payload factor, range, and flight segment (e.g., taxi-idle, takeoff, climb, cruise, and approach). In addition, the EIs of CO, hydrocarbons, NO_x and other emitted species must be evaluated for each flight segment for use in the scenario calculations.

Supersonic aircraft such as the Concorde generally fly a Breguet path; the cruise altitude increases continuously as the fuel is used. On the other hand, subsonic aircraft generally follow regulated paths of constant-pressure altitude. It is assumed, in the scenarios to be developed, that the HSCTs will also fly a Breguet path.

Fuel Consumption

The amount of fuel burned by the HSCT fleet in the assessment scenarios, it is assumed, is largely determined by aircraft performance parameters. In a complete economic scenario, these parameters are interrelated and must be accurately predicted. For example, a high estimate in aircraft drag would also lead to higher operating costs, higher ticket prices, and a decrease in

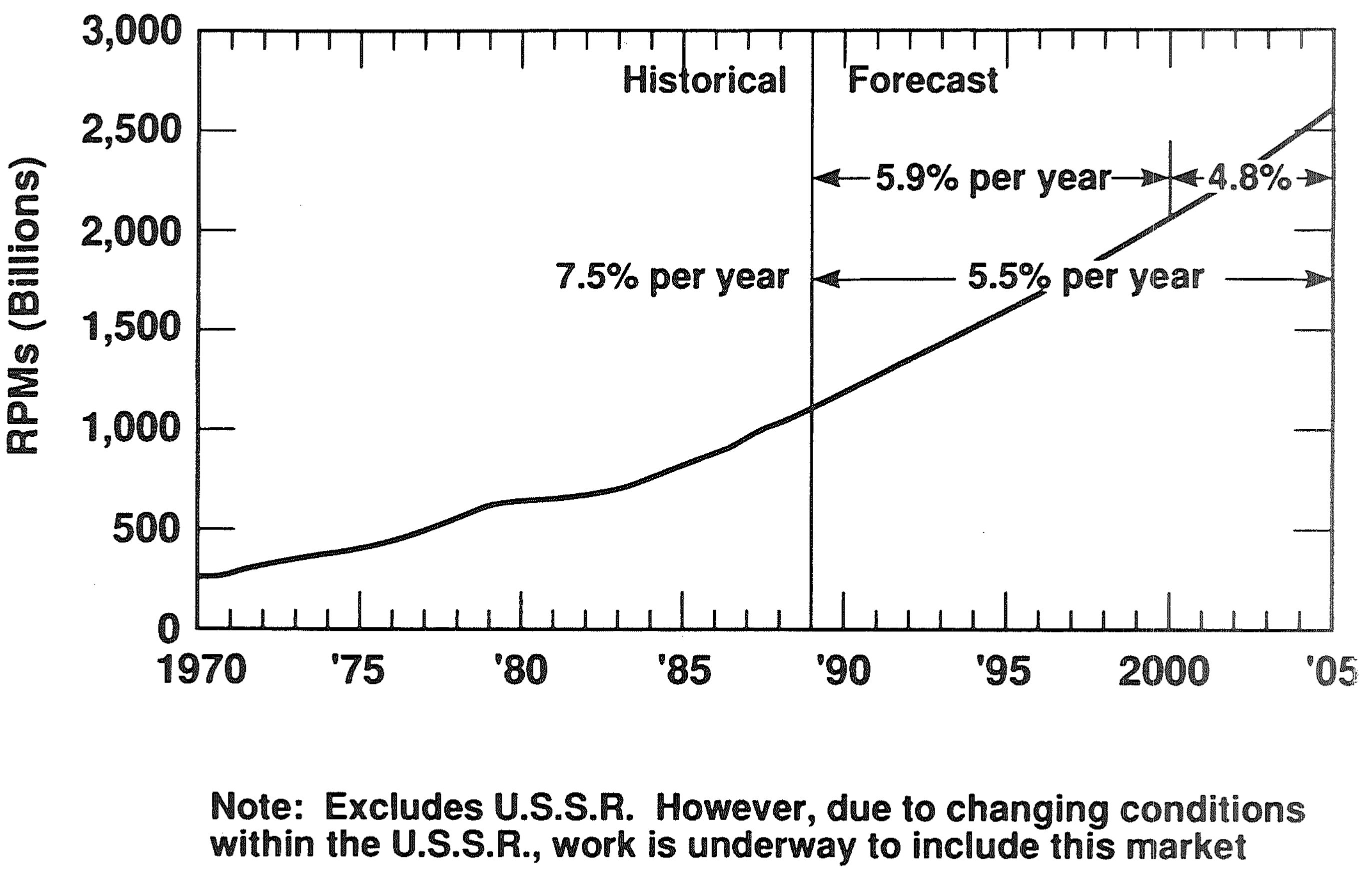


Figure 1. World air travel forecasts in revenue passenger miles, based on Boeing (1).

passenger demand, thus moving toward a lower fleet fuel burn. These contrasting trends, for an apparently simple parameter like aerodynamic drag, illustrate the complexities involved in estimating the total annual fuel burn in marketing projections for a supersonic aircraft fleet.

We shall avoid having to consider the interplay between ticket costs and available seats being flown by HSCTs by specifying a minimum fleet of aircraft operating at maximum efficiency (i.e., number of hours in the air).

Engine Emissions

The primary engine exhaust products from commercial jet aircraft are carbon dioxide and water vapor. Secondary exhaust products include nitrogen oxides (NO_x), carbon monoxide (CO), hydrocarbons, and sulfur divide (SO_2). (See chapter 2 for a thorough review of emissions.) The relative amounts of NO_x, CO, and hydrocarbons depend on engine operations, particularly the thrust setting of the engine, and those at cruise conditions will differ significantly from those observed at takeoff and climb.

At this time, it appears that the use of alternative fuels would likely be too expensive because they would mean higher operating costs and because airports would have to be improved to handle such fuels. Therefore, the HSCTs considered here (Mach 1.6-2.4) use some form of Jet-A fuel. A report by Boeing (2) analyzed a set of 53 jet fuel samples obtained worldwide, and found that Jet-A consists of a range of hydrocarbons with a mean molecular weight of 164. The average hydrogen content was 13.8%, by weight.

The average sulfur content of the analyzed Jet-A samples was 0.042% by weight ($EI(SO_2) = 0.8$). Sulfur content of jet fuels depends on the refinery processes used to produce the jet fuel. Since sulfur poisons some of the catalysts used in refining, several of the advanced processes have led to significantly reduced sulfur levels. With increasing environmental regulation of aromatic content and sulfur impurities in fuels, it is likely that sulfur content in jet fuels will be reduced further.

The emission levels from aircraft engines are defined in terms of EIs, measured as grams of emission per kilogram of fuel burned. Emissions of water vapor, carbon dioxide, trace metals, and sulfur dioxide are essentially independent of combustor operation conditions and are solely a function of fuel composition. On the other hand, EIs for nitrogen oxides, carbon monoxide, and hydrocarbons depend on the combustor design and thrust settings for the engine (see chapter 2). There has been confusion in the past about the definition of an EI for NO_x; this problem can be avoided if this EI is defined precisely (see chapter 2) as the weight of NO_2 (in grams per kilogram of fuel) plus the weight of NO as converted to NO_2. This definition is consistent with the recommendations of the International Civil Aviation Organization and the FAA, and it is used throughout the HSRP.

BACKGROUND ATMOSPHERE

Atmospheric model calculations (3-6) have shown that the sensitivity of stratospheric ozone to HSCT emissions is dependent on the background atmosphere (particularly on the amount of total reactive chlorine, Cl_y, in the stratosphere). It is therefore important that model calculations for the year 2015 HSCT scenarios consider appropriate background concentrations of atmospheric constituents. The current rates of increase for many important atmospheric constituents are known reasonably well. It is also possible to project (with greater uncertainty) the effects of international controls on the production of chlorofluorocarbons (CFCs) over the next few decades. It should also be recognized, however, that it becomes increasingly uncertain, as trace gases predictions are extended into the future.

Table 1 shows (for the years 1990 and 2015) suggested tropospheric concentrations of long-lived trace constituents that influence the stratosphere. The projections for 2015 are based on scenario C of the 1991 assessment of stratospheric ozone now under way for the United Nations Environment Programme and the World Meteorological Organization. This background atmosphere assumes near-global compliance with the international agreements, including the CFC substitutes. This projection of the 2015 atmosphere will likely evolve as our knowledge of trace gas concentrations and budgets are improved; for example, the atmospheric composition listed in Table 1 has been updated since the calculations in chapter 5 were set. Sensitivity analyses using other trace gas concentrations may also need to be considered in future modeling studies.

Table 1. Suggested Background Atmosphere for Current (1990) and Projected (2015) Scenarios*

Species	1990	2015
CO_2	354 ppmv	411 ppmv
CH_4	1.8 ppmv	2.1 ppmv
N_2O	310 ppbv	330 ppbv
CH_3Cl	600 pptv	600 pptv
CFC-11	280 pptv	270 pptv
CFC-12	485 pptv	545 pptv (+110 pptv)†
CFC-113	57 pptv	81 pptv
CCl_4	106 pptv	74 pptv
CH_3CCl_3	159 pptv	17 pptv
HCFC-22	104 pptv	71 pptv
Halon-1211	2.5 pptv	0.9 pptv
Halon-1301	3.5 pptv	5.3 pptv
CH_3Br	15 pptv	15 pptv
Total Cl	3.6 ppbv	3.4 ppbv
Total Br	21 pptv	21 pptv

*This proposed composition differs from that used in the sensitivity studies in chapter 5, which were set at an earlier date. The background scenario for 2015 is based on Scenario C for the 1991 UNEP-WMO Ozone Assessment Report (in preparation), and assumes near-global compliance with the international agreements, along with inclusion of CFC substitutes (HCFCs, but treated as CFC-12 in the scenario).

† Additional 110 pptv of CFC-12 is included to account for the additional chlorine in the stratosphere resulting from HCFCs.

SUBSONIC EMISSION SCENARIOS

This section addresses the developments required for projecting emissions from the subsonic fleet for the 2015 period, as well as those necessary for analyses of the global atmospheric effects from past and current subsonic emissions. Limited model studies (3,5,6-8) have shown that the effects on tropospheric ozone from increases in subsonic emissions over the last several decades could be significant and need further examination (although this is not currently part of the HSRP Program). Improved analyses of current subsonic emissions, while inherently different from the projected HSCT emissions, still provide a useful test for evaluating model predictions.

Very limited information is available on past emissions. An analysis of aircraft emissions for the year 1975 was made by Athens et al. (9) and revised by Oliver (10). The overall accu-

racy of these analyses is unknown. Boeing has calculated emission scenarios for the year 1987, based on published subsonic commercial jetliner flights. They have also developed projections of emissions for commercial subsonic flights for the 2015 period. These scenarios have been documented in detail in a NASA report (1). All of the published analyses provide estimates of emissions as a function of altitude and latitude, but not longitude or season; only scheduled commercial passenger flights have been included. The methodology used by Boeing is described next.

Boeing 1987 Subsonic Emissions Scenario

Subsonic fleet emissions for 1987 were calculated using the airline fleets and schedules in the 1987 Official Airline Guide (OAG). The calculations considered only scheduled commercial passenger jet aircraft. Airplane types and flight frequency data were prepared and combined with the applicable fuel burn and emission data.

A total of slightly more than 29,000 city-pairs were considered; the total for weekly departures was 229,794. For simplification, subsonic aircraft flights were divided into two groups, depending on range. Approximately half the flights are flown with stage lengths of 400 statute miles or less. The mean altitude of these flights was defined to be 26,000 feet (about 7.9 km). Flights longer than 400 nautical miles were considered to have an average altitude of 37,000 ft (about 11.2 km). All aircraft were assumed to cruise at one of these two altitudes. Fuel consumption was calculated assuming a constant average fuel flow over the entire flight profile.

Fuel burn and emissions were calculated as follows. From the OAG data, 32 jet airplane types were considered, and their characteristics were tabulated. For each aircraft type, fuel burn and emissions were calculated for average fuel burn over a great circle route between all city-pairs served by that type and were grouped into 10° latitude bands. The EIs used were appropriate for cruise power settings, would be higher during the takeoff and climb segments, and would be lower during the descent and landing segments of the flight. The results of the calculations of total fuel consumption and the distribution of fuel consumption as a function of latitude are shown in Table 2.

Domestic flights in the Soviet Union, Eastern Europe, and China are not included in the OAG and thus were not included in the 1987 scenario. Scheduled commercial air cargo and turboprop commercial flights were also not included in the scenario. Further, the 1987 subsonic fleet scenario included only 58% of the scheduled commercial passenger departures. The other 42% were aircraft with turboprops and reciprocating engines; these are primarily low-altitude, short-range flights. In addition, the scenario did not include charter, general aviation (private), or military flights. Our scenario for the assessments clearly must include a more complete set of data on subsonic flights.

Boeing Subsonic Emissions Scenario for 2015

The composition of the subsonic fleets for the years 2000 and 2015 were assumed to have average stage lengths and service patterns comparable to the current (1987) aircraft types (i.e., new jet transport types would replace same capacity/range aircraft). Using the Boeing long-range forecasts of available seat miles (ASM) for these types and the average stage length and service patterns of these types, the number of departures was calculated for the years 2000 and 2015, using the 1987 ASM level as a base.

Future aerodynamic performance, fuel consumption, and emission characteristics of the generic subsonic fleet were estimated and described in detail in Boeing (1). The emissions data for the year 2000 was estimated by assuming that technology improvements would allow an average 100° F increase in combustor inlet temperature, with a resulting 20% increase in NO_x emissions.

Table 2. Total Fuel Consumption and Fractional Distribution of Fuel Use as a Function of Latitude Band for Commercial Jet Air Traffic, 1987 and 2015 (projected)*

	1987 (Subsonic)		2015 (Subsonic)		2015 (Subsonic + HSCT)		
Latitude Band	**Subsonic at 26 kft**	**Subsonic at 37 kft**	**Subsonic at 26 kft**	**Subsonic at 37 kft**	**Subsonic at 26 kft**	**Subsonic at 37 kft**	**Supersonic at 60 kft**
80-90°S	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
70-80°S	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
60-70°S	0 00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
50-60°S	0.03%	0.02%	0.00%	0.01%	0.00%	0.01%	0.00%
40-50°S	0.50%	0.10%	0.18%	0.15%	0.18%	0.13%	0.00%
30-40°S	1.60%	1.54%	1.30%	2.03%	1.29%	1.79%	2.81%
20-30°S	2.18%	1.51%	1.97%	1.61%	1.76%	1.54%	1.87%
10-20°S	1.05%	1.82%	0.38%	1.62%	0.38%	1.44%	2.24%
0-10°S	2.08%	1.74%	1.06%	1.68%	1.07%	1.66%	2.20%
0-10°N	2.62%	2.29%	1.60%	2.35%	1.63%	2.04%	8.99%
10-20°N	3.93%	4.07%	2.87%	3.69%	2.90%	3.30%	8.62%
20-30°N	7.85%	11.43%	5.86%	11.03%	5.95%	12.10%	8.48%
30-40°N	36.62%	30.64%	45.64%	31.66%	44.99%	32.40%	15.83%
40-50°N	29.48%	25.79%	27.43%	25.13%	27.98%	27.07%	30.91%
50-60°N	10.41%	15.69%	10.32%	15.67%	10.46%	13.54%	13.94%
60-70°N	1.63%	2.89%	1.38%	2.85%	1.40%	2.61%	1.36%
70-80°N	0.02%	0.38%	0.00%	0.41%	0.00%	0.30%	1.46%
80-90°N	0.00%	0.09%	0.00%	0.10%	0.00%	0.07%	1.27%
Total(10^{10} kg/yr)	1.14	7.24	1.71	1.52	1.63	1.48	6.59

*Data as analyzed by Boeing. Year 2015 air traffic distributions are shown for both a projected subsonic only fleet and for a fleet consisting of both subsonic and HSCT aircraft.

For the Year 2015, it was assumed that further increases in combustor inlet temperature would be offset by lower-NO_x, technology combustors, so the only increase in emissions would derive from growth of the fleet. The results of the calculations of total fuel consumption, and the distribution of fuel consumption as a function of latitude, are shown in Table 2.

Development Needs

The available emissions scenarios have recognized limitations that need to be addressed over the next several years. It is critical to have accurate estimates of the changes in emissions from the subsonic fleet in the upper troposphere. Although secondary in importance, such analyses are needed to test current atmospheric models, as well as to improve the understanding of environmental effects from existing aircraft emissions.

Data Grids and Traffic Seasonality

Existing subsonic scenarios do not provide variations in emissions with longitude. While this is satisfactory for the 2-D models used for most analyses of aircraft effects, 3-D models will be used in HSRP assessments in the future. These calculations will require that emissions be expressed as a function of longitude and time of year, as well as altitude and latitude. The grid

structure needed for emissions will vary, depending on the models being used in the assessment.

The Boeing subsonic scenarios have assumed that all aircraft fly at one of two different altitudes. These scenarios need to be reevaluated using the actual flight patterns of the aircraft. Such scenarios can then be used to determine more accurately how much of the subsonic emissions are currently injected into the stratosphere.

There are no analyses of the effects resulting from seasonal variations in the subsonic emissions; however, seasonal variations in emissions are likely to have an impact on the predicted changes in ozone and should be included in the scenarios developed for subsonic emissions. At mid and high latitudes, the height of the tropopause varies dramatically with season. In addition to the effects in the troposphere, seasonal variations of current emissions in the lower stratosphere, particularly at high latitudes in the winter and spring, are of interest because of the possible interactions with the chemistry influencing ozone in the polar vortex.

Inclusion of Air Cargo, Military, and Other Aircraft

The Boeing scenario for subsonic emissions scenarios considered only published flights of commercial passenger jet aircraft. Based on jet fuel production estimates (11), the fuel consumption calculated by the Boeing 1987 subsonic emission scenario was only 53% of the total world jet fuel usage. Data on fuel production makes several estimates possible: aviation in the U.S.S.R. and Eastern Europe could account for 12% of the world total, while China could account for 2%. Estimates of U.S. military aviation fuel and U.S. private jet use account for 7% each. From these estimates, approximately 19% of the world jet fuel usage is still unaccounted for, but is probably allocated to charter, cargo, and turboprop aircraft. Cargo (freight) flights may account for a high fraction of the missing fuel use; this requires further analysis. Available forecasts suggest that air freight traffic will increase more rapidly than passenger traffic (12).

Estimates of the distribution of past, current, and future subsonic emissions will need to account for military aircraft, U.S.S.R. aviation, Chinese aviation, the worldwide cargo fleet, and perhaps commercial turboprop aircraft as well (although these probably fly too low for their emissions to be important globally). Unfortunately, such estimates are not currently available for inclusion in assessment studies.

PREVIOUS HSCT SCENARIOS

In spite of the renewed interest in building HSCT aircraft, only a limited number of scenarios have been developed for analyzing the potential effects from these aircraft. The most recent of these are the matrix of HSCT scenarios developed for this report (see chapter 5). Johnston et al. (4) performed a series of sensitivity analyses to examine the range of possible HSCT emissions, but no attempt was made to develop realistic scenarios. As part of NASA's initial study in 1989, Boeing (1) and McDonnell Douglas (13), developed a series of HSCT scenarios, which were used in atmospheric modeling studies by Ko et al. (5) and Isaksen et al. (6). More recently, Wuebbles and Kinnison (3) worked with McDonnell Douglas to develop and analyze the effects on ozone from a broad-based matrix of HSCT scenarios, assuming realistic flight paths with varying cruise altitudes and amounts of NO_x emissions; these scenarios are similar in concept, but not the same, to those that have been developed for this report.

The assumptions used by Boeing and McDonnell Douglas in their scenarios differ in several respects. To provide a historical perspective for further scenario development, this section describes the approaches used by Boeing and McDonnell Douglas in the development of their previous HSCT scenarios.

Boeing Projection

The introduction of the HSCT should lead to the replacement of some long-range subsonic aircraft. It was assumed in the total projected fleet that the long-range subsonic fleet would be reduced so as to keep the same total fleet ASM capacity as that of an all subsonic fleet. In a free economic market, the HSCT fleet size will depend on the extent to which the aircraft can (1) meet environmental requirements, (2) exceed capacity and range requirements of the airlines, and (3) compete economically with long-range subsonic aircraft. However, for these atmospheric effects studies, Boeing assumed a baseline scenario such that, by the year 2015, there would be a fleet of 625 HSCTs with a payload of 247 passengers, a cruise speed of Mach 2.4, an average stage length of 3400 nautical miles, and a utilization of about 9 hours per day. The baseline HSCT aircraft assumed 69,449 lb of fuel per hour (~18 km) at cruise conditions with a 65% payload. The average cruise altitude was estimated to be 60,000 ft.

Using Boeing's airline scheduling computer code, 235 market (city) pair routes were modeled. Fuel burn calculations were made for 10° latitude bands, with waypoint routing to avoid sonic booms over land. During over land flights, aircraft were assumed to cruise at Mach 0.9 and at a lower altitude. For those cases, the fuel use was consigned to 37,000 ft. The fuel use and latitudinal distribution for one of the year 2015 scenarios is given in Table 2.

McDonnell Douglas Projection

The overall procedure used by McDonnell Douglas in their HSCT scenario development for generating the annual fuel burn results is shown in Figure 2. In a general sense, the procedure shown in Figure 2 can be thought of as consisting of three basic steps: (1) estimate of location (altitude × latitude) of fuel burn; (2) estimate of amount of fuel burn; and (3) calculation of NO_x molecules (and other constituents) from engine company EIs. These steps are explained in detail here.

Estimate of Location (Altitude × Latitude of Fuel Burn)

The latitude and altitude of exhaust injection are a function of the worldwide route structure assumed for future HSCT operations and the mission flight profiles of the global flights. The HSCT will compete in the long-range passenger market. This consideration, combined with concerns about passenger traffic forecasts and over land operations, led to the selection of 10 International Air Transport Association (IATA) regions (out of 18 total worldwide) that appear to be appropriate for supersonic transport aircraft operation. For each of these 10 major flight routing regions, a representative city-pair was selected that best represents the average range and latitude distribution of flights in that region. The 10 regions, and the corresponding city-pairs, are shown in Figure 3.

A flight profile for the HSCT configuration under study is generated for each of the 10 city-pairs. The flight profile is 3-D with the flight path using great circle flight profiles. As seen in Figure 3, 7 of the 10 routes can be considered flights over water, while 3 are predominantly over land. The flight profiles (and fuel burns) for the overland routes do not account for operational constraints (i.e., subsonic), nor are the flight paths altered to avoid operation over land.

Estimate of Total Fuel Burn

The total fuel burn in a given region is a function of the passenger demand and load factor (i.e., percentage of seats occupied on a given flight) projected for that region. The number of flights per year were then calculated in the McDonnell Douglas scenarios by dividing the total fuel burn by the fuel burn of a single flight. The fleet size can then be determined based on the number of flights, aircraft speed, and turnaround time. The competitive position of an HSCT,

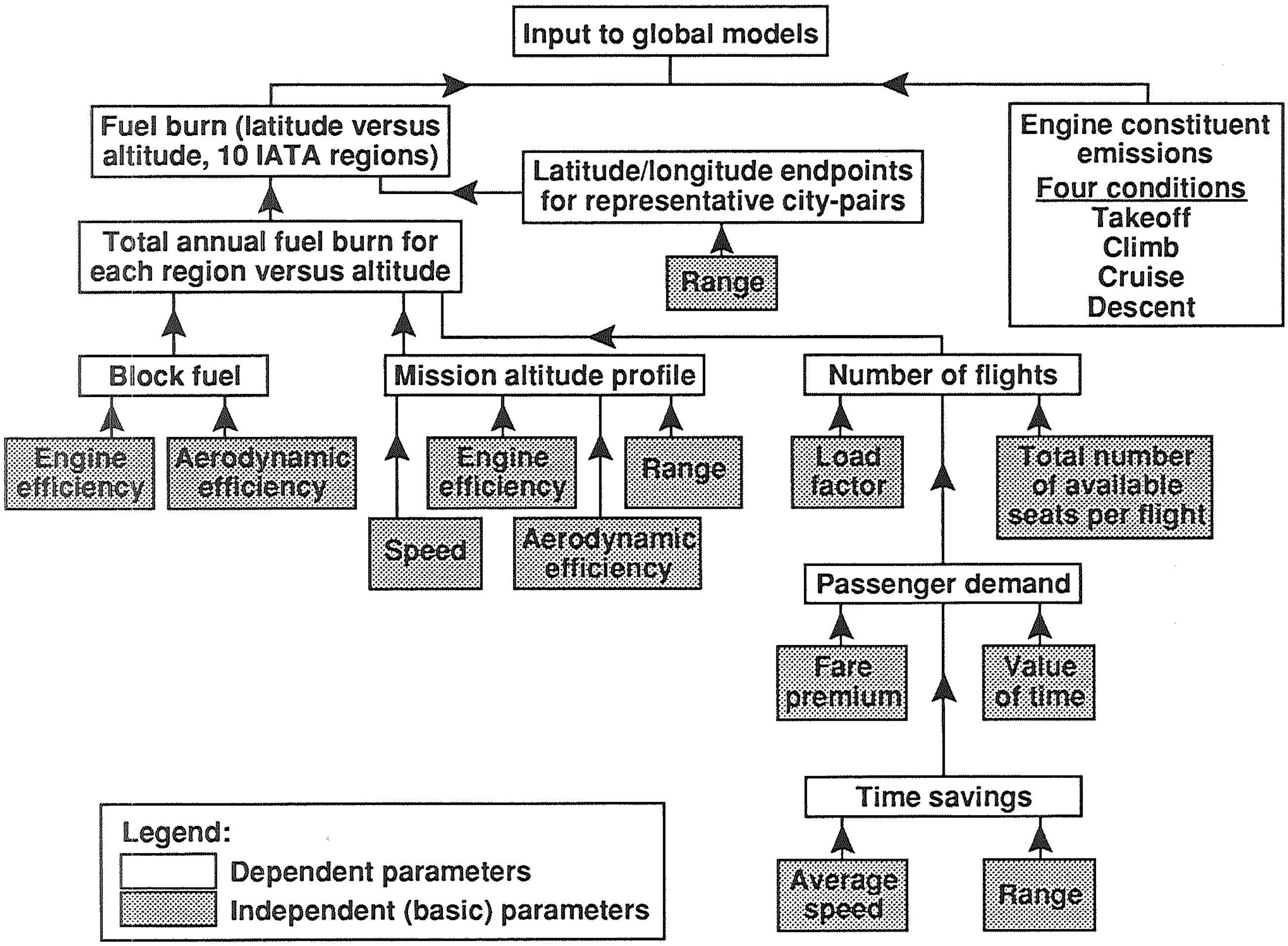
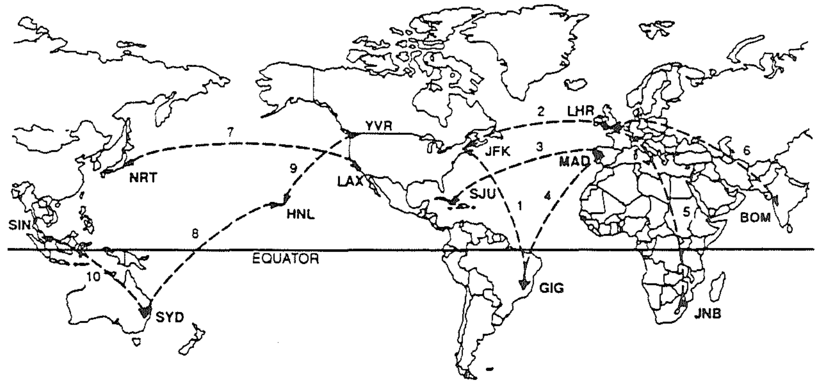


Figure 2. Data Flow for chart used by McDonnell Douglas for generating HSCT emission scenarios.



Region		City-pairs
1	North-South America	New York – Rio de Janeiro (JFK-GIG)
2	North Atlantic	New York – London (JFK-LHR)
3	Mid-Atlantic	San Juan – Madrid (SJU-MAD)
4	South Atlantic	Rio de Janeiro – Madrid (GIG-MAD)
5	Europe Africa	Johannesburg – London (JNB-LHR)
6	Europe Far East	Bombay – London (BOM-LHR)
7	North and Mid-Pacific	Los Angeles – Tokyo (LAX-NRT)
8	South Pacific	Honolulu – Sydney (HNL-SYD)
9	Intra-North America	Honolulu – Vancouver (HNL-YVR)
10	Intra-Far East and Pacific	Singapore – Sydney (SIN-SYD)

Figure 3. HSCT representative city-pairs used by McDonnell Douglas.

with respect to the subsonic fleet, was determined by contrasting the fare premium associated with supersonic flight with the time savings available through it. The time savings for a given flight is a function of the average speed and total distance of the flight. Thus, in the Mach 1-3 range, the passenger demand for an HSCT increases with increasing cruise speed and range. The total annual fuel burns and load factors by region for the three HSCT baseline configurations used by McDonnell Douglas are shown in Table 3.

To arrive at the most conservative scenario for emission (i.e., largest HSCT fuel use), the McDonnell Douglas group assumed a zero fare premium for HSCT flights and a 50% market capture for HSCT in the 10 regions under consideration.

Once the total fuel burn by region has been determined, it is superimposed on the 3-D route structure grid as determined previously. This results in 10 matrices, each showing the annual fuel burn data by altitude and latitude for one of the IATA regions. These matrices are summed together to produce one matrix that displays the total annual global fuel burn for an HSCT fleet by latitude and altitude.

Calculation of Aircraft Emissions

The calculation of NO_x emissions in a given altitude/latitude grid cell is a relatively simple calculation based on the NO_x EI (EI NO_x) of the engine under the appropriate operating conditions. The operating condition of the engine varies considerably over the flight profile, and hence it is not desirable to simply apply one EI NO_x (e.g., cruise) over the entire flight regime.

For a first-order approximation, it can be assumed that the engine cycle varies with downrange distance or altitude. There are, essentially, four stages to a Mach 3.2 HSCT mission profile: takeoff and subsonic climb (0-10 km), supersonic climb (10-18 km), cruise (18-24 km), and descent (24-0 km). These components are illustrated in Figure 4. The engine operating cycles approximately correspond to these four conditions.

Table 3. Total Annual Fuel Burned by Region for HSCT Baseline Configurations, as Used in HSCT Scenario by McDonnell Douglas

Region	Load factor (%)	Total annual fuel burn (1,000 kg)		
		Mach 1.6 Fleet size = 436	Mach 2.2 Fleet size = 440	Mach 3.2 Fleet size = 363
1. North-South America	63	786,220	789,075	847,345
2. North Atlantic	69	9,104,480	9,167,462	9,897,685
3. Mid-Atlantic	70	656,924	660,546	711,389
4. South Atlantic	70	1,028,543	1,025,231	1,087,798
5. Europe-Africa	61	1,972,390	1,996,343	2,177,999
6. Europe-Far East	79	3,093,521	3,097,565	3,310,548
7. North and Mid-Pacific	73	10,905,871	10,879,303	11,550,727
8. South Pacific	73	1,187,339	1,190,235	1,275,625
9. Intra-North America	68	72,579	74,320	82,751
10. Intra-Far East and Pacific	72	4,723,051	4,785,222	5,221,580

To map out the injection of NO_x and other constituents into the atmosphere more accurately, a different set of EIs is used for each of the four conditions. These are stratified by altitude, except for descent, which spans all of the flight altitudes from the top of cruise to ground level. To account for this overlap, the constituent EIs for descent are factored into the takeoff, climb, and cruise indices, based on the ratio of time spent in a particular altitude band while descending. The ratios based on a Mach 3.2 mission are shown in Table 4, but note that such ratios will change with the Mach number. EIs (for NO, NO_2, etc.) provided by engine manufacturers are used with these ratios, resulting in three sets of indices for the stratified altitude bands. The number of molecules of a given constituent at each altitude-by-latitude grid point is calculated from the total fuel burn and the appropriate EI.

FUTURE HSCT SCENARIO REQUIREMENTS

The HSCT scenarios documented here were developed using a simplified approach. Several of the assumptions used by Boeing and McDonnell Douglas in conducting their independent HSCT scenario calculations are being jointly reexamined for future scenario development. The increasing sophistication of global atmospheric chemical-transport models will also require the improvement of both the geographical and altitude resolution of the emission scenarios.

Table 4. Flight Profile Characteristics for a Typical Mach 3.2 Mission, as Used in HSCT Scenarios Developed by McDonnell Douglas

Altitude band	Time spent (%)		
	Takeoff and climb	Cruise	Descent
0–10 km	59.5	—	40.5
10–18 km	49.8	—	50.2
18–30 km	1.1	94	4.9

This section discusses a consolidation of the Boeing and McDonnell Douglas approaches, and it also describes further modifications to the HSCT scenario considered necessary for increasing the accuracy and resolution of the environmental assessments. A common framework must be established that will meet the needs of the NASA HSRP program, of the aircraft industry, and of the atmospheric modeling community. The following methodology, and resultant scenarios, will be fully documented and remain in the public domain; there is no intention in this assessment to develop scenarios as proprietary engineering trade studies for the aircraft manufacturers.

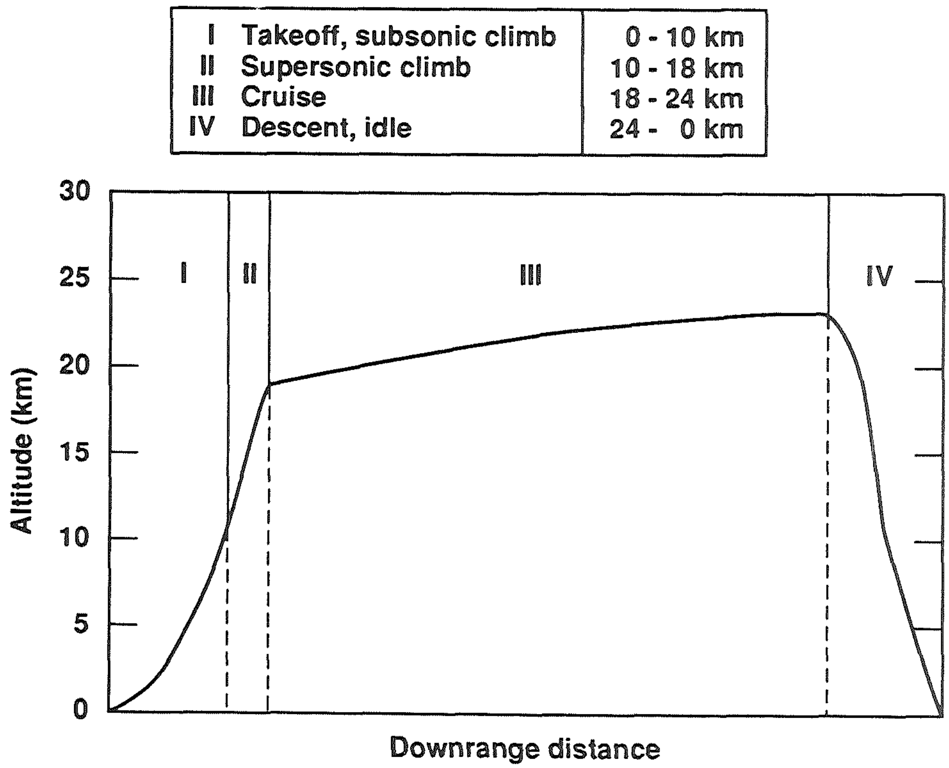


Figure 4. Four stages of Mach 3.2 mission profile considered for engine emissions in HSCT scenarios developed by McDonnell Douglas.

The goal is to generate realistic 3-D scenarios for a relatively mature HSCT fleet and the coexisting subsonic fleet in the year 2015. As a reference, a scenario for a 2015 fleet that has only subsonic aircraft (no HSCTs) will also be determined.

FLEET ASSUMPTIONS

HSCT City-Pair Network

In the earlier work, Boeing and McDonnell Douglas used quite different networks of city-pairs. For future work, a common city-pair network needs to be established. This should include at least 150 city-pairs chosen to adequately represent the global network for air travel demand — including both the subsonic and supersonic routes, and also considering both passenger and cargo flights. Boeing and McDonnell Douglas, in conjunction and coordination with the HSRP, are working to define a network and the associated city-pairs. At this time, the exact roster of city-pairs has not been fully agreed upon.

Fleet Size

Fleet size projections vary according to the performance characteristics of the HSCT and the operating costs, relative to subsonic aircraft. Factors that will influence these projections include aircraft configuration (number of passengers and class mix), speed and productivity of the aircraft, utilization and scheduling, range, and specific fuel consumption. Thus, the technical design of the aircraft and its required performance are strongly coupled to the perceived market and the operating costs of the aircraft. With the preliminary HSCT designs considered to date, many of these details are still unresolved. *The resolution of these marketing assumptions is not necessary for the assessments needed for environmental impact statements.*

The scenarios developed for the HSCT fleet in 2015 will assume that there are approximately 500 aircraft. Although sensitivity studies with atmospheric models should also consider the possibility of additional HSCT aircraft at years beyond 2015, this date provides a good benchmark for evaluating the potential environmental effects. However, if 500 aircraft were found to be environmentally acceptable, while determinations showed that more aircraft were unacceptable, regulatory actions could be used to prevent the global HSCT fleet from growing further, or lower-emissions engines could be required.

One aim for the scenario development will be to establish the minimum size of an economically viable HSCT fleet (i.e., the number of planes that must be sold to at least break even). *The environmental assessment can reasonably be based on this minimum number of HSCTs, since a smaller number (if predicted) would not be built and a larger number, if in demand, could be constrained by environmental regulations.*

Mode of Operation

Supersonic flight may have to operate in a restricted environment because of concerns about atmospheric effects, sonic boom, and community noise. These may include cruise altitude restriction, restrictions over land, and dedicated flight corridors. Possibly, such restrictions will affect range, fuel burn, and fleet size. Future scenarios should examine the potential ramifications of such restrictions.

HSCT emission scenarios should be designed so that the algorithm for flight paths can be adjusted to regulations (e.g., use waypoint routing to avoid supersonic flight over land or fly subsonically unless a means is found to reduce sonic boom) or to other criteria such as meteorology (e.g., search for tailwinds), or a combination of regulations and meteorology (e.g., optimize the flight path with wind fields to minimize stratospheric injections).

Supersonic Operation by the Military and Others

Countries that have supersonic military aircraft may use specific operational supersonic corridors to minimize the impact of the sonic boom over land or else use over water operational areas cleared by air traffic control. An evaluation of the magnitude of current and projected military supersonic operations may be appropriate.

Any potential for supersonic air cargo or charter flights should also be examined.

Polar Routes

Several of the projected supersonic routes are Arctic routes. Because of the unique meteorological conditions of the stratospheric winter polar vortex, the effect of cross-polar routes should be assessed. In the future, there may be a need to reconsider the choice of Arctic routes based on the assessment.

MODELING METHODOLOGY

Data Grids and Traffic Seasonality

Today, two-dimensional models are the workhorses of global stratospheric chemical-transport modeling. These 2-D models represent the longitudinally averaged atmosphere on a latitude-altitude-grid, typically, 5°-10° (or more) by 1-3 km. More comprehensive three-dimensional stratospheric chemical-transport models are at an early stage of development. To support the current 2-D and future 3-D atmospheric models, emissions should be provided on a variable grid with a resolution at least as fine as 5° longitude $\times$ 4° latitude $\times$ 1 km altitude. However, the assessment scenarios should be developed so that they can be mapped onto any grid appropriate for such models. Since the resolution of these models varies from model to model and is expected to become finer as a function of increasing computing capabilities, the emissions scenarios need to be developed with algorithms that are spatially continuous. The scenarios developed will then be mapped onto the grids appropriate to the assessment models.

As mentioned earlier, expected seasonal variations in emissions may have an important impact and will need to be included in the scenarios.

Future Test Cases

Industry is currently focused on developing basic HSCT technology, with some effort dedicated to considering alternative HSCT designs. The next several years will still be too soon to optimize the design options based on either economic or environmental criteria. The technology risk, cost, and performance are sensitive functions of the aircraft speed. Because of aerodynamic drag, the speed of the aircraft essentially determines the optimum cruise altitude of the aircraft. Thus, high Mach-number aircraft fly at higher altitudes than low Mach-number aircraft. We know from the earlier Climatic Impact Assessment Program (1975) studies (14), as well as more recent modeling studies, that the environmental impact is a sensitive function of the injection altitude. Thus, the flight altitude has the most significant effect on both the airplane design and on the atmospheric evaluation. At this time, we are considering HSCTs with a cruise speed between Mach 1.6 and 2.4. For a given cruise speed and the other specified criteria discussed earlier, the turnaround time and the amount of time the aircraft actually spends in the air is dependent on aircraft cruise speed and will be represented in the scenarios developed.

The question of whether to use a fraction of the total ASM (i.e., seats flown on a great-circle route between city-pairs) or fixed fuel burn as a criterion in the scenario development has

been highly controversial. In general, as the HSCT's speed (and thus cruise altitude) varies, fuel consumption and the economics of the aircraft both change. While an assumption of fixed ASMs for the HSCT might seem attractive, it does not realistically reflect the development of the technology or of the economics of a commercially viable HSCT fleet. Only predictions of ASMs for the total commercial aviation fleet can be meaningfully predicted. On the other hand, given the range of flight operations criteria to be considered (per earlier discussion), it is also not appropriate to fix the amount of fuel burned for the HSCT fleet.

However, having specified the number of aircraft (approximately 500) and given a passenger load of about 300 passengers per aircraft (range, 250 to 350), we can readily develop a definition for fixing passenger demand flow (PDF), defined as the product of seats flown between city-pairs times the direct great-circle distances. The flight speed (Mach number) and average turnaround time will also need to be considered. Therefore, *PDF will be fixed based on this criterion.* An outstanding issue will be the method of allocating between HSCT and subsonic flights among long-range flights.

The process for developing scenarios for this next assessment needs to be open ended. *The primary criterion for developing realistic scenarios for aircraft emissions is to prepare the best scientifically based assessment of the environmental impact of a projected HSCT fleet.* There are too many unknowns currently associated with the HSCTs and their flight operations to impose exacting specifications on the scenario development. The scenario development methodology must also be responsive to the improving understanding of atmospheric processes and to the needs of the HSRP program; the scenarios are to be an active database. As a secondary criterion, a matrix of scenarios like the one developed for this report, but with better-defined flight criteria, would provide meaningful information to HSCT designers. It is also important that a detailed scenario be calculated for at least one HSCT design to accurately account for the geographical and altitude distributions of HSCT emissions.

Summary of HSCT Scenario Methodology

Here is a summary of the methodology determined in this chapter for future HSCT scenarios.

Methodology

The general methodology for calculating realistic emissions scenarios, as previously developed by Boeing and McDonnell Douglas, will continue to be used to determine the emissions from the year 2015 aircraft fleet. Refinement of previous methods will be implemented to meet the needs of the assessment and the atmospheric models, as outlined in the text.

It is important to recognize that the assessment scenarios are an active database that must be publicly documented and available. They will continually be scrutinized, and the approaches used will be reevaluated. The methodology needs to be flexible to the scenario-related needs of the scientific, engineering, and policy-making communities.

The final emissions scenarios should be generated from a set of algorithms, beginning with the demand for air travel between city-pairs, and including a conceptual HSCT, routing algorithms, and EIs, among others.

The scenarios and algorithms developed for the NASA HSRP program are considered to be in the public domain.

Passenger Demand Flow	Total HSCT Passenger Demand Flow will be fixed, as defined in the text. Actual fuel used and ASMs will be determined by the conceptual HSCT chosen. Military, air cargo, and charter flights will be included.
HSCT Cruise Speed	Assume HSCTs will fly between Mach 1.6 and Mach 2.4.
Number of Aircraft	Approximately 500 HSCT aircraft with 250 to 350 passengers per aircraft.
City-Pair Network	At least 150; actual city-pairs to be determined.
Flight Performance	Includes realistic modeling of climb, cruise, and descent.
Operation Restrictions	Allow for use of adaptable algorithms that can account for waypoint routing (to avoid supersonic over land flights), for other environmental considerations, or for meteorological considerations.
Traffic Seasonality	Must be evaluated and included.
Data Grids	Scenarios should be developed from algorithms (e.g., flight performance, routing) that are continuous in spatial resolution and then mapped onto appropriate grids for the atmospheric models.

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